

Research With The U.S. Army Centrifuge

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ABSTRACT: The U.S. Army Engineer Waterways Experiment Station (WES), located in Vicksburg, Mississippi, has recently installed a uniquely powerful and large centrifuge. Although much of the recent worldwide interest in centrifuge modeling has concentrated on geotechnical problems, the new WES centrifuge facility will address research needs in physical modeling across the full range of engineering applications. The purpose of this paper is to describe the WES centrifuge, to discuss current research being conducted in the centrifuge facility and our vision for the future. The research described here will focus on field problems involving dynamics particularly earthquake work and blast loading. However, the WES centrifuge is uniquely broad-based in its research applications; many types of field problems, involving fluid-flow, heat transfer, and cyclic and static loading are being addressed in a wide range of fields: geotechnical, structural, environmental, hydraulics, coastal engineering, and engineering for cold regions. Some initiatives in these areas are also described.

1 INTRODUCTION

The WES has a long history of physical modeling. Its pioneering research in the early 1930s in areas of hydraulics engineering and flood control used scaled physical models carved in the loess soil. Hydraulic physical modeling experiments which replicated such historic locations as the Los Angeles Harbor, the New York Harbor, Niagara Falls, and the Old River Control Structure on the Mississippi River have been conducted throughout its 65 years of service to the Army and the Nation.

During the past several decades, with the advent of analog and digital computers, WES moved into the numerical modeling arena. With the rapid advance in computer technology leading

to PC's and supercomputers, research is now being conducted using numerical modeling techniques including finite difference, finite element, discrete element, and discontinuous deformation analysis. Recent accomplishments include the development of a three-dimensional water quality model for the entire Chesapeake Bay, the use of complex three-dimensional codes to investigate cratering and air-blast effects from explosive events, and the use of two-dimensional effective stress finite element analysis for predicting large deformations occurring in embankment dams as the result of earthquake induced liquefaction in the dam and/or its foundation material.

The WES centrifuge is capable of spinning a payload of up to 8 tonnes and achieving accelerations of up to 350 gravities (g). This

centrifuge provides a physical modeling capability that greatly enhances research techniques. Case histories and/or physical model experiments are required to validate numerical computer codes. Physical models have the advantages of being controllable, relatively inexpensive, and provide better known conditions than field cases.

Researchers can better control the material properties and boundary conditions of physical models. The cost of centrifuge experiments is far less than full-scale field experiments which may involve hundreds of thousands or millions of dollars.

2 MODELING FIELD PROBLEMS IN A CENTRIFUGE

Physical modeling of field problems generally involves the construction and experimentation with scale models of a prototype or field structure. The response of the model to a physical perturbation such as cyclic loading, earthquake, ocean waves, explosion or even freezing or groundwater changes can be measured and interpreted in terms of the field problem under consideration. Realistic model behavior data can provide valuable information for designers about failure mechanisms and long term performance.

In many engineering fields, particularly geotechnical engineering, gravitational effects dominate performance. Where the behavior of a material is stress dependent, such as with the engineering properties of soil, then simple scaling of a field problem and experimental investigations on the laboratory floor will give erroneous results. For example, in a slope failure it is common to observe cracking near the ground surface where the confining stresses are low but the shear stresses are high, rupture along a slip surface at greater depth and finally flow at depth as the confining pressure increases still further and the shear stress ratio reduces to a value below the

critical state or characteristic threshold value, (Figure 1).

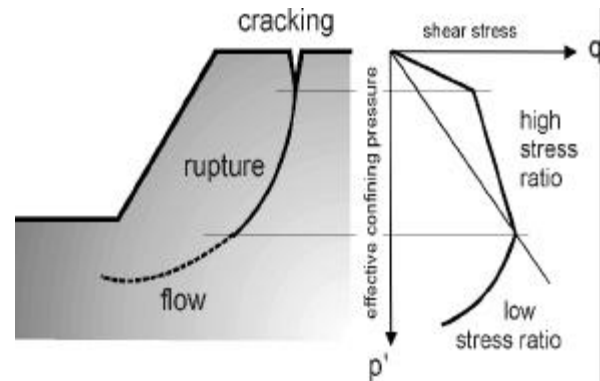


Figure 1. Ratio of shear stress to confining pressure governs soil behavior.

If one were to attempt to model the slope failure in Figure 1 on the laboratory floor at 1/50 scale without the benefit of a centrifuge, the effective confining stresses in the soil would be 50 times less than those same stresses in the field and hence could bring the full depth of soil in the model into a region where tensile fracture (or cracking) dominates.

The use of a centrifuge however, overcomes this modeling error by increasing the weight of each particle in the model by an equivalent number of gravities. Generally the linear scale of the model and the number of gravities are chosen to be identical. Therefore, a 1/50 scale model of a 20 m high earth slope would be 400 mm high. Under a steady acceleration of 50 gravities (approximately 500 m/s^2), it would have identical self-weight stresses at equivalent points in the model and in the prototype. The behavior of the miniature slope will then mimic the behavior of the prototype. Each soil element in the centrifuge model is subject to the same stress path as its equivalent element in the full-scale prototype.

Figure 2 shows a silt slope failure in remolded Vicksburg loess, carried out on the WES centrifuge. Details of the failure can be seen,



Figure 2. Failure of a silt slope in Vicksburg loess.

including the cracking near the top of the slope, and rupture along the slip surfaces that run nearly parallel to the slope. The response shown is typical of loess behavior with no deep-seated flow movement.

Scaling relationships can be derived from physical principles that interpret the centrifuge model experimental investigation data in prototype terms (Schofield 1980 and 1981, Schofield and Steedman 1988). These are summarized in Table 1.

As a technique for solving engineering problems, the use of the centrifuge was first pioneered in the United States (US) and in the Soviet Union during the 1930s (some references claim the concept of a centrifuge model can be traced to the 19th century or earlier). Although the idea did not fully develop in the US at that time, the Soviets recognized its potential in the area of weapons effects and developed a major program of centrifuge modeling. It is understood that this continued until the recent political changes.

In the west, the development of centrifuges for study of geotechnical problems was led by academic researchers in the United Kingdom (UK) committed to the study of soil as a plastic material.

Table 1. Centrifuge scaling relations		
Parameter	Field	Centrifuge Model (Ng)
Stress	F	F
Strain	ϵ	ϵ
Length, displacement	L	L/N
Area	A	A/N ²
Force	F	F/N ²
Volume	V	V/N ³
Mass	M	M/N ³
Energy	E	E/N ³
Frequency	f	Nf
Velocity	v	v
Acceleration	a	a/N
Time (for inertial events)	t	t/N
Time (for diffusion events)	t	t/N ²

A number of centrifuge centers developed in the UK, US and in Europe during the 1970s and 1980s primarily attached to universities or research institutions.

Miniature instrumentation and, recently, the development of affordable advanced data acquisition systems have revolutionized the potential for centrifuge models. Model experiments can now provide detailed quantitative information on the response of a model at many different points for comparison with numerical models or analytical solutions. Miniature instrumentation has already been developed which can measure displacements, pore fluid pressures, accelerations, resistivity, wave height, shear wave velocity, and so on. 'In-flight' site investigation tools can perform cone penetration probes, vane shear experiments or other explorations of the 'site'. Miniature cameras can observe the behavior of the structure in close up. Systems can load the

soil and structures, trigger earthquakes, generate water waves, freeze ice sheets, carry out staged construction, release contaminants or detonate explosives.

The wide range of physical phenomena that may be created in a centrifuge and the quality and detail of the data that may be captured from a model in-flight clearly provides substantial opportunities for engineering research studies. The Corps of Engineers has been involved with centrifuge modeling since the 1970s, and the recent development of the WES Centrifuge Research Center in Vicksburg demonstrates the Army's full commitment towards the use of physical modeling as an integral part of engineering analysis.

3 THE WES CENTRIFUGE

The design specification of the centrifuge followed a review of available academic facilities which had shown that none were able to routinely conduct experimental models of the large field structures and problems with which the Corps is principally concerned (Ledbetter, 1991). The facility was therefore designed with a unique operating envelope. It was required that model containers should be easily placed on and off the centrifuge and these requirements led to the design of a beam centrifuge with a swinging platform based on the French designed Acutronic 661, 665, and 680 series of geotechnical centrifuges. Other centrifuges in this Acutronic family include one at Rensselaer Polytechnic Institute, Troy, New York, at the Centre for Cold Oceans Resources Engineering, St. Johns, Newfoundland, and several in Japan and Europe. Figure 3 shows the WES Centrifuge in its containment structure; key parameters are listed in Table 2 and Figure 4 shows the performance envelope relating payload capability to centrifugal acceleration. Prototypes of the order of 300 m in breadth and 300 m deep can be simulated in models subjected to up to 350 gravities (around 3500 m/s²).

Table 2. Key characteristics of the Army centrifuge	
Gravity range	10 to 350 g
Platform radius	6.5m
Payload at 143g	8000kg
Payload at 350g	2000kg
Centrifuge capacity	1144 tonnes

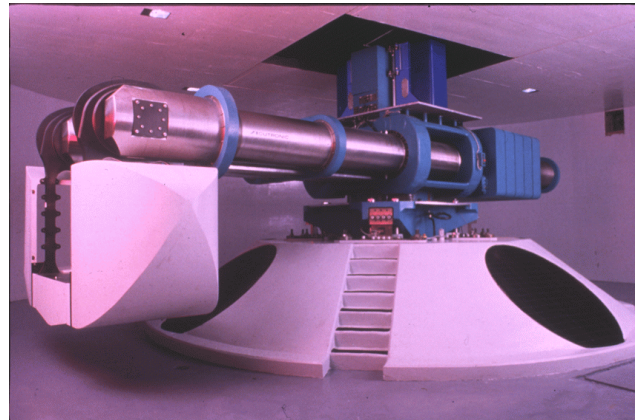


Figure 3. The U.S. Army centrifuge at the Waterways Experiment Station.

A wide range of modelling capabilities was required and actuators and appurtenances have been designed to fulfil these requirements. Models can be constructed in a range of containers that depend on the geometry of the problem under investigation (plane strain, axi-symmetric, three dimensional, etc.) and the type of phenomenon to be recreated.

Recent worldwide interest in centrifuge modeling has concentrated on geotechnical

applications; however, the WES centrifuge facility has a much broader mission. The WES centrifuge will address research needs in physical modeling across the full range of engineering applications. Investigations are possible under climatic conditions ranging from desert to polar to ocean regions. Key capabilities include: (1) force and displacement controlled load systems, (2) earthquake simulation, dynamic vibration loading and water wave generation, (3) blast loading, (4) model package environmental control, (5) in flight manipulation of the model materials and fluids, (6) miniature instrumentation, cameras and in flight site interrogation, and (7) high speed data acquisition and control systems.

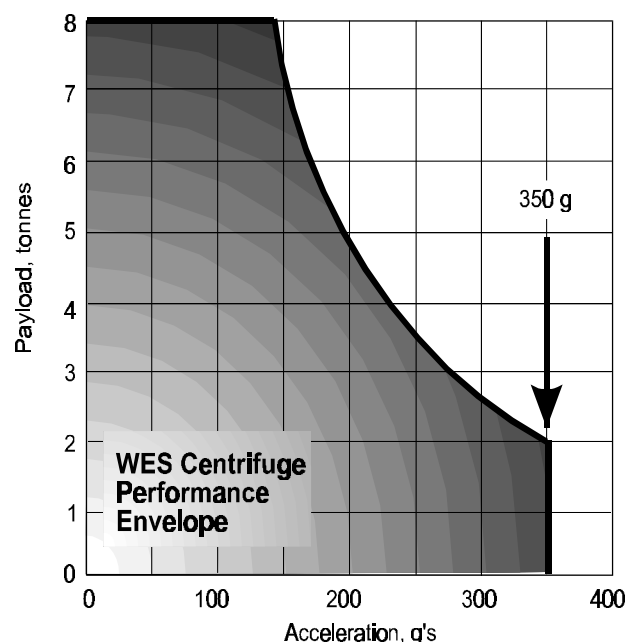


Figure 4. WES Centrifuge performance envelope.

The new capabilities that will flow from the centrifuge will depend on the ingenuity of its users and the design of its appurtenances. In this respect the design of the centrifuge itself is merely one component of the development of new capabilities in physical modeling.

4 CENTRIFUGE MODELING OF DYNAMIC PROBLEMS

The use of centrifuges to address field problems involving dynamics dates back many years. As noted above, the Soviets made use of centrifuges as early as the 1930s and 1940s for the study of weapons effects. WES, which first used centrifuge modeling for cratering studies in the 1970s, has now developed the capability for carrying out such explosive investigations on its new centrifuge (as discussed further below).

In the field of earthquake modeling, Professor Mikasa at the University of Osaka pioneered the development of the first centrifuge 'earthquake' actuator by using a tilting mechanism to create a pseudo-static lateral acceleration field on a soil model in flight, (Mikasa et al. 1969). Steedman (1991) provides a review of the application of the centrifuge to dynamic geotechnical studies which highlights some of the important achievements of Japanese researchers in earthquake centrifuge modeling.

Since the 1980s, a variety of actuators have been developed around the world for the simulation of earthquake-like base shaking on centrifuge models. These have ranged from sophisticated units using servo-hydraulic systems to provide broad band shaking input to less mechanically complex systems that can apply a broadly sinusoidal base shaking motion of a given duration and frequency. In general, limitations posed by the high gravitational field in which the equipment must work and the high development cost has restricted the use of servo-hydraulic systems to low g centrifuge applications and small models. At WES, the requirement to conduct experimental models of large field problems has led to the development of a robust mechanical shaker designed to operate at over 200 gravities, significantly higher than any earthquake centrifuge modeling on other beam centrifuges carried out to date. Early indications, using a prototype version of the system developed together with Cambridge University, have provided encouraging results, as seen in Figure 5.

The WES earthquake shaker (Figure 6) uses the angular momentum stored in high speed rotating

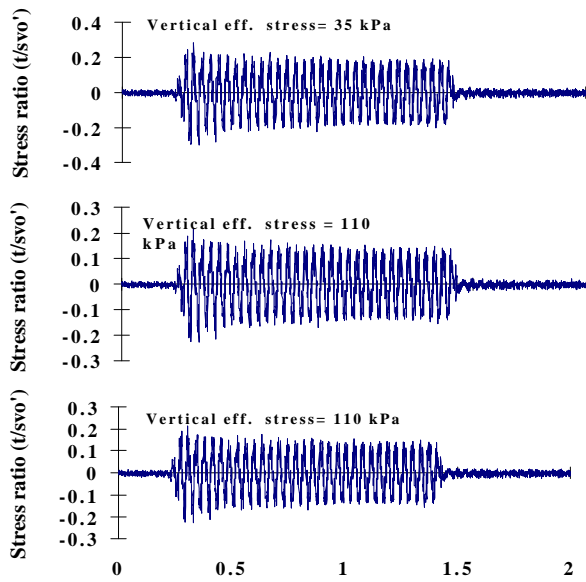


Figure 5. Shear stress ratio at two depths in a WES soil model under dynamic loading at 50 g

flywheels to provide the energy source for the shaking motion. Power is transferred from the flywheels to the base plate beneath the model via a continuously oscillating shaft which is briefly grabbed by a high-speed clutch for the desired duration of excitation. Shown in Figure 7 is the earthquake shaker mounted on the centrifuge. Figure 8 shows the equivalent-shear-beam laminar model container that is 900 mm in length, 650 mm in height and 355 mm in width. This container

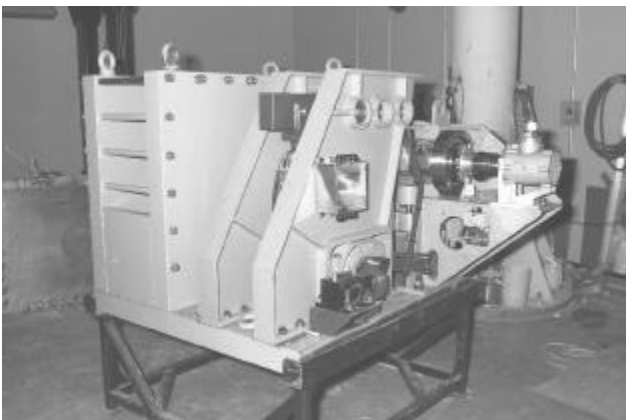


Figure 6. The WES dynamic load actuator

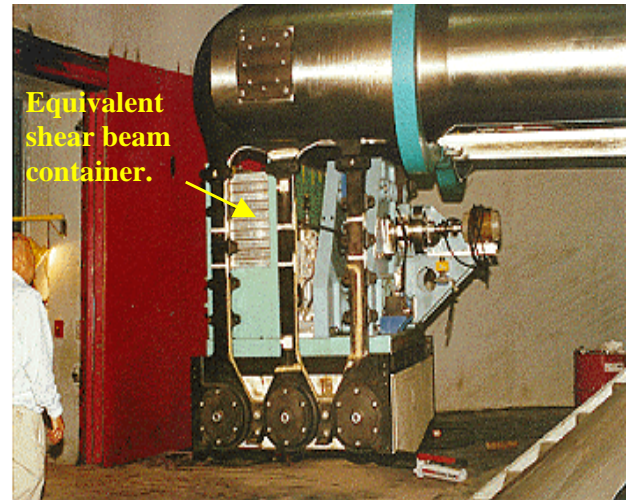


Figure 7. Earthquake shaker on the centrifuge

incorporates shear sheets on each of the end walls to transfer the complementary shear stresses generated on vertical planes in the specimen by base shaking in the horizontal direction. This improves the uniformity of shear.

From Table 1 it is seen that as the g level is increased it is necessary to increase the frequency of shaking and simultaneously to reduce the amplitude of motion. At high g levels these small displacements may become comparable to the manufacturing tolerances of the moving parts; particular attention has been paid to this issue in the design of the WES shaker. The resulting system is robust and economic, and will provide a



Figure 8. Equivalent shear beam model container

pre-programmed duration and frequency of shaking.

In fields such as the seismic design of retaining walls, centrifuge model studies have provided valuable insights into the mechanisms underlying the onset of permanent movement and the ultimate failure of different forms of wall. Conventional approaches to the prediction of permanent movement of monolithic walls have been investigated and refined using centrifuge model behavior data (Steedman and Zeng 1996). Other studies have investigated the point of application of the dynamic force increment and the consequences of the development of excess pore pressures and liquefaction in the backfill behind anchored walls (Steedman and Zeng 1990). Figure 9 shows a model of an anchored sheet-pile wall experiment conducted at WES for Oregon State University.

A key area of interest to WES has been the study of liquefaction and the dynamic response of embankments and dams. WES has made extensive



Figure 9. Model anchored sheet pile wall dynamic load experiment.

use of centrifuge modeling in this field to provide realistic data for the validation of numerical codes and other analyses and a substantial program of research is planned for the new facility. Figure 10 presents typical results from recent experiments in a test program investigating the effects of confining stress on liquefaction that could have a significant impact on dam earthquake stability and safety.

The WES involvement and interest in centrifuge earthquake engineering experiments and studies dates back about twenty years to collaboration with the University of Cambridge (Morris 1979). WES conducted experiments in the 1980s of models including dry and saturated embankments with and without surface supported and embedded structures.

An important advantage of centrifuge earthquake experiments is the wealth of data and information that can be acquired. The measured responses shown in Figure 10 cannot be obtained by any other means under the equivalent prototype stress states and provide valuable insight to behavior under earthquake excitation and for numerical model development and verification.

Other fields involving dynamic loading that have been addressed using the centrifuge include dynamic loading of foundations (>machine vibration), (see Laue and Jessberger 1994), and wave loading on coastal defences and seabed deposits (Sekiguchi et al. 1994).

The modeling of instability of sand beds caused by water waves at g has been hampered by the need for very large or deep wave tanks. At high g it becomes practical to adopt viscous scaling of the pore fluid because of the small size of the wave

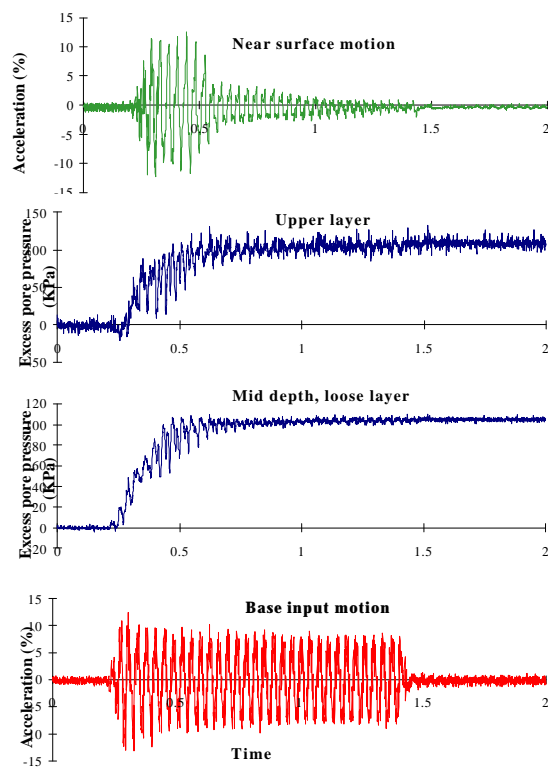


Figure 10. Dynamic load experiment time history raw data from pore pressure transducers and accelerometers.

tank, and researchers at Kyoto University have shown that using this technique, wave induced liquefaction can be reproduced in a sand bed deposit, (Sekiguchi et al. 1994). This class of problem will also be addressed in future at WES.

5 CURRENT RESEARCH AT WES

A number of research projects using the centrifuge are currently underway at WES. In the following paragraphs, a few of these investigations are described which demonstrate the Corps interest in a wide range of applications. Some of these fields are entirely new to centrifuge modeling.

In the field of earthquake engineering, a large study has commenced to investigate aspects of the prediction of liquefaction. This has the potential for a major impact on the design of remedial

measures for earth dams in seismic areas in the US. To date, the factors which strongly influence the prediction of a soil to liquefy and its residual strength as used for design purposes have been evaluated only on laboratory element test data and fortuitous field performance data. The new research approach is to use the new large earthquake shaker mounted on the WES centrifuge to conduct a series of models experiments, monitoring the development of excess pore fluid pressure in the foundation soils directly as a function of the density, amplitude of shaking and number of load cycles (Figure 10). This approach will not need to extrapolate design factors from small laboratory samples and may lead to significant improvements in design and analysis techniques.

A second research program is concerned with the gravity driven mixing and flow of immiscible fluids as oils seep into the natural groundwater environment. The purpose of the models is to acquire data suitable for the validation of numerical models of DNAPL (denser than water non-aqueous phase liquid) movement in groundwater, the development of which have been hampered by the lack of realistic experimental or field data. In a centrifuge model under high gravity, the time taken for a diffusion event is reduced by the square of the model scale over the equivalent time in the field. This occurs because of the small physical size of the model and the higher hydraulic gradients. This is a strong advantage for any experiments investigating long term diffusion type problems as the centrifuge can achieve in a few hours what would take many years to tens of years of monitoring in the field.

The first centrifuge experiments undertaken by the Corps in the 1970s were in the field of blast crater modeling. More recent work has studied the effects of blast and blast induced liquefaction on structures. Figure 11 shows a blast precision-scale cratering experiment model configuration. Figure 12 shows a crater formed in dry sand in the blast chamber on the WES centrifuge, with a buried charge equivalent to 500 lb. of high

explosive (PETN). The model, at 45 gravities, has a crater diameter of 300 mm, equivalent to 13.5 m in the field. Figure 13 shows a cut cross-section through the crater and model of Figure 12. Shown in Figure 14 is a comparison of crater profiles from field experiments and centrifuge precision-scale experiments.

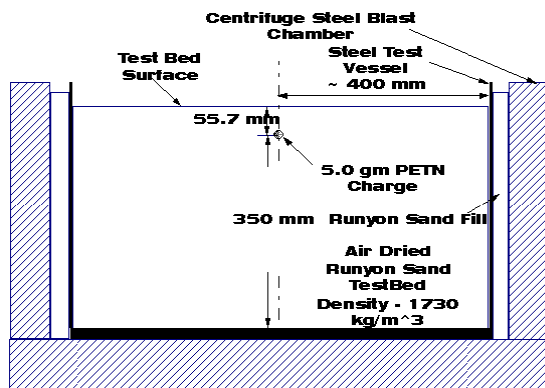


Figure 11. Precision-scale cratering experiment model.

The WES centrifuge has a substantial capability for modeling the effects of explosions on a wide range of structures, again benefitting from the capability to operate at up to 350 gravities. In the scaling of blast phenomena, energy scales with N^3 , Table 1, and hence 1 gm of high explosive at 100 gravities will generate an event equivalent to a 1 tonne explosion in the field. At 350 gravities, large explosions can be replicated. The program of work in blast modeling includes simulation of field events to demonstrate internal consistency of the models and the effects of explosions on a range of structures and facilities in different ground conditions.

Engineering for cold regions is another field of interest in the Corps and in this area studies have commenced concerning the effects of ice forces on structures with the growing of an ice sheet under increased gravity in a specially designed insulated

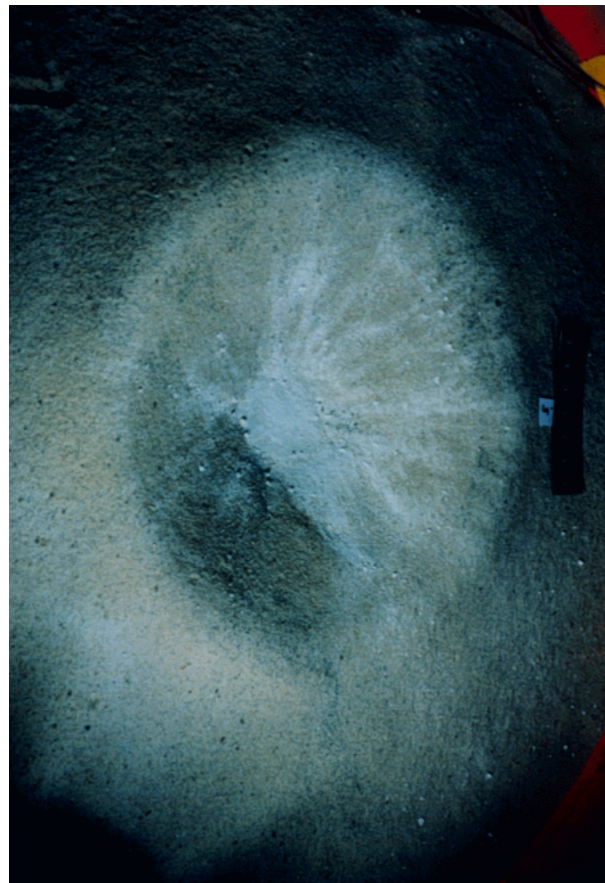


Figure 12. Precision-scale crater experiment conducted at 45 g centrifugal acceleration.



Figure 13. Cross-section through the crater of Figure 12.

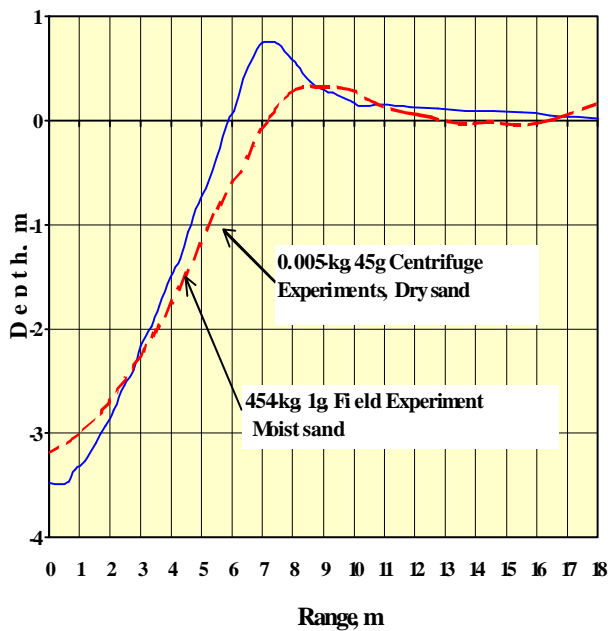


Figure 14. Comparison of crater profiles, field and centrifuge precision-scale experiments.

container. Earlier studies at Cambridge University have shown that ice grown under increased gravity in the laboratory has an internal structure like that of a multi-year ice sheet in the Arctic, with a profile of snow on the surface, random crystals at shallow depth and vertically oriented crystals below that. If ice sheets of similar form to those found at sea can be formed in a centrifuge model then this pioneering research may provide a new route altogether for the development of engineering solutions for cold regions engineering.

In the environmental area, a research program has been initiated to investigate the consolidation of dredged material and the consequential damage to capping layers. Initial experiments have addressed the long-term settlement of the material. Continuing experiments are investigating the movement of contaminants. As was noted earlier, small volumes of material in a centrifuge can replicate large volumes in the field. For contaminant migration investigations, this means that even small samples, which can be readily managed in the laboratory, can provide a basis for realistic modeling and simulation of the behavior of the full-scale prototype. Samples can be used this way

rather than simply used to acquire parameters in a laboratory element test. Experiments on the WES centrifuge have replicated 20 years of contaminant migration.

6 VISION

The development of the WES Centrifuge Research Center marks the transition of centrifuge modeling from a pure geotechnical engineering research tool to a modeling technique of wide application in engineering work. The Centrifuge Research Center aims to become the worlds leading centrifuge modeling facility supporting the Corps of Engineers, the Army, the Department of Defense, other federal agencies and other nations, collaborating with academic and industrial organizations and addressing novel and demanding engineering problems worldwide.

In order to make this vision a reality, WES is developing vehicles to foster partnerships with researches and colleagues from Government, Industry and Academia. The Corps has an agreement with the National Science Foundation to facilitate such partnerships. WES is also developing vehicles to foster partnering with owners, operators, contractors, and designers who have problems that could be addressed using data obtained from the results of centrifuge studies.

7 CONCLUSIONS

The WES is continuing its tradition of 65 years of physical modeling with the acquisition of the most powerful centrifuge known to date and the development of unique applications and appurtenances for conducting research. Centrifuge investigations are possible across a wide range of engineering fields. Research is being conducted in earthquake engineering, environmental problems concerning groundwater flow, geotechnical engineering, blast phenomena, cold regions and ice formation, dredge material disposal behavior, and contaminant migration. Research is planned in the engineering areas of soil-structure interaction

(behavior of large lock structures), hydraulics and coastal (wave loading on beaches and seabeds), and airfield pavements. The Corps is convinced that numerical and physical modeling must progress together to solve today's and future engineering problems. The centrifuge will allow us to investigate phenomena not previously feasible including the performance of large civil engineering structures up to and beyond their design limits and long term prediction of environmental problems.

The WES centrifuge modeling capability marks the transition in centrifuge development from academic research to broad application in engineering research and problem solving. The increase of gravity in a centrifuge and its influences on physical processes provides great benefit for modeling field phenomena. The opportunities for application to physical processes are limited only by imagination.

8 ACKNOWLEDGMENTS

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